Development of AlGaN Based UV LED and Lasers (λ~280nm)

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Road to AlGaN based UV Laser

Why AlGaN?

•Current UV gas and solid state lasers include XeCl(308nm) or KrF(248nm) excimer lasers, N_2(337nm), He-Cd (325nm) or SHG-Ar(257nm)

•AlGaN alloy is useful for UV optical devices because of its wide bandgap and direct transition emission between 3.4eV and 6.2eV. Its wide transition range covers the lasing wavelength achieved by the existing UV lasers.

•UV semiconductor lasers are more attractive in comparison with solid state and gas lasers because of their small size, long life time, high efficiency and CW lasing operation.

Development of AlGaN Based UV Laser (λ~280nm)

Issues		Research work needed
High Al% compounds	→	• Develop high temperature growth and equipment • Parasitic reactions
Non-radiative defects in high Al% compounds	→	• Study defects & deep levels • Model defect energetics
Low electrical conductivity for such high Al%	→	• New doping schemes • New dopants • Reduce defects & deep levels

Development of AlGaN Based UV Laser (λ~280nm)

Issues		Research work needed
Material parameters unknown	→	• Achieve more consistent material quality within research community
Radiative recombination mechanisms unknown	→	• Systematic study of optical properties: cathodoluminescence, UV photoluminescence, ...
Low refractive index difference ($\Delta n<0.3\sim0.4$)	→	• New laser device structures

Development of AlGaN Based UV Laser (λ~280nm)

Issues | Research work needed

More intense piezoelectric effects in high Al% heterostructures

- Calculate & model piezo effects
- New laser device structures

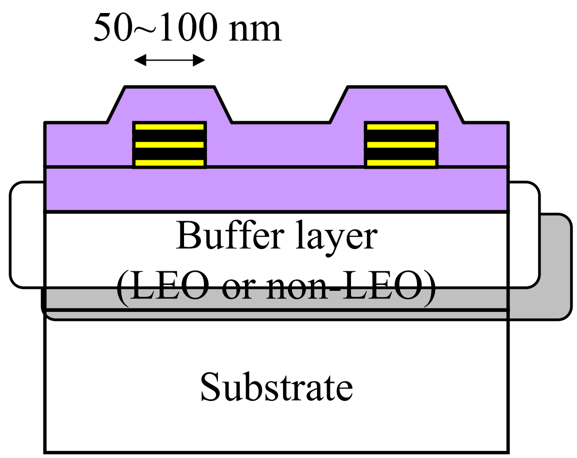
But there is one hope:

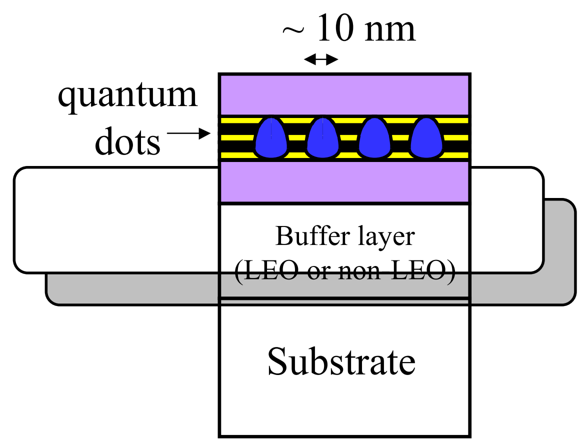
Development of AlN substrates is promising (< ~5 more years)

Conceptual Approach & Uniqueness

Material quality improvement

- Defect reduction (LEO) ⟷ **Selective area epitaxy**
- Novel p-type doping schemes ⟷ **Superlattices**





Novel laser structure designs

- Narrow buried ridge laser ⟷ **Localized epitaxy**
- Quantum dot laser ⟷ **Localized epitaxy**

Why QD(0D) Vs. Bulk(3D)?

QD are attractive for their linear and non-linear optical properties because:

- A perfect population inversion can be achieved due to the discrete nature of energy levels

- Energy level quantization is accompanied by the concentration of bulk oscillator into single spectral lines and small volumes
(spectral weight of QD transition/spectral weight of bulk exciton

$$= \frac{a_0^3}{V} \propto \text{ Reciprocal of the confinement volume)}$$

a_0: Bohr radius
V: QD volume

- Disappearance of the temperature dependence broadening mechanism (that dominates RT QW) in QD as an immediate consequence of electronic state confinement.

On the road to nano-scale structure development

There are a number of ways quantum dots can be generated
Examples are:

- Self-assembled
(suffers from dots of different sizes and a non-uniform distribution)

- Generation of dots of various sizes by re-growth in electron-beam lithography defined holes
(to define individual dots of quantum sizes one needs to use low energy beam EBL system to achieve low beam current. The time required to cover a large area of a wafer with appreciable number of holes can exceed 24 hours!)

- Use of lift off technique to define QD from individually exposed holes
(in addition to a long exposure time this method requires additional processing step: metallization)

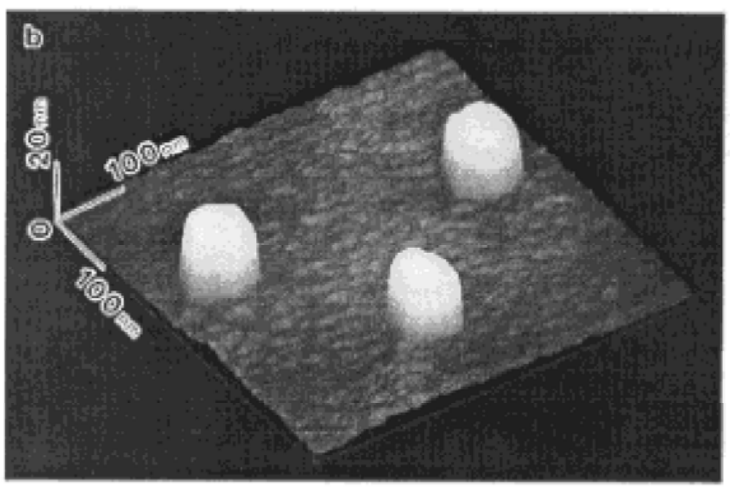
- Defining dots using direct writing exposure technique. (the most promising method due to shorter exposure time and less number of processing steps.)

III-Nitride Nano-scale structures reported in the literature

Self-Assembled GaN and InGaN Quantum dots

Self-assembled (Ga, InGa)N QD have been fabricated with[1] and without[2,3] using a surfactant

GaN QD/AlGaN using a surfactant[1]



Emission from InGaN QD[3]

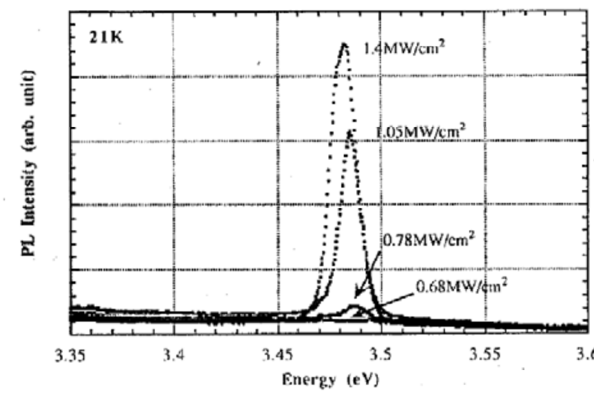
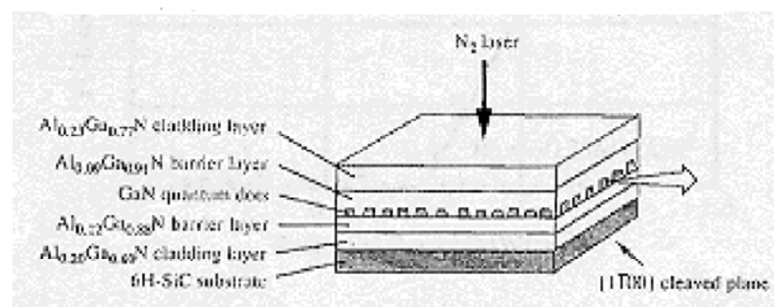


FIG. 3. Side emission spectra from the GaN quantum dots with a cavity length of 1 mm under power densities of 0.68, 0.78, 1.05, and 1.4 MW/cm^2. The threshold power density I_{th} was determined to be ~0.75 MW/cm^2 at 20 K.

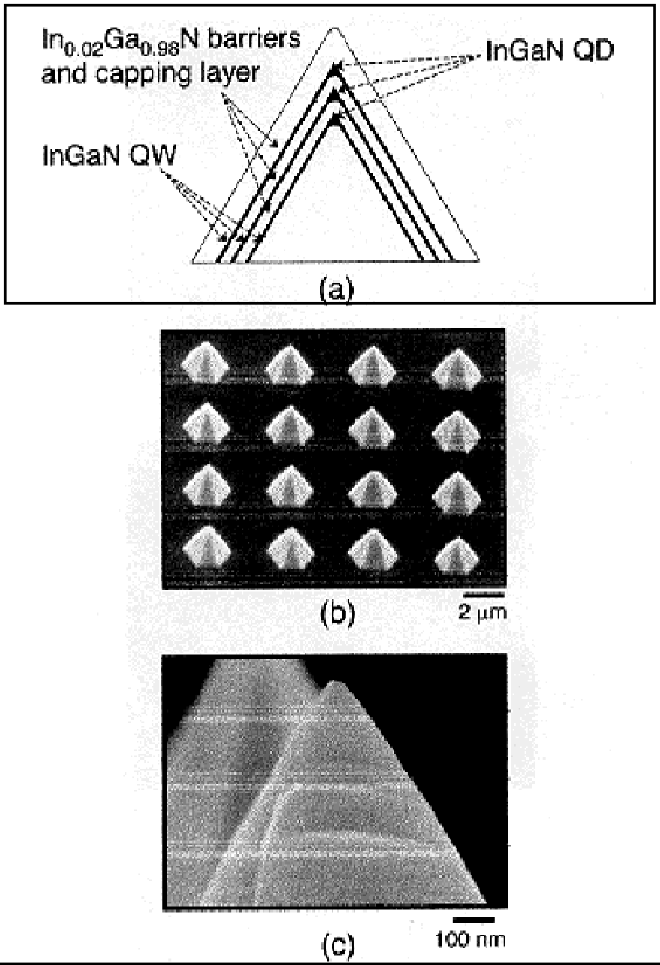


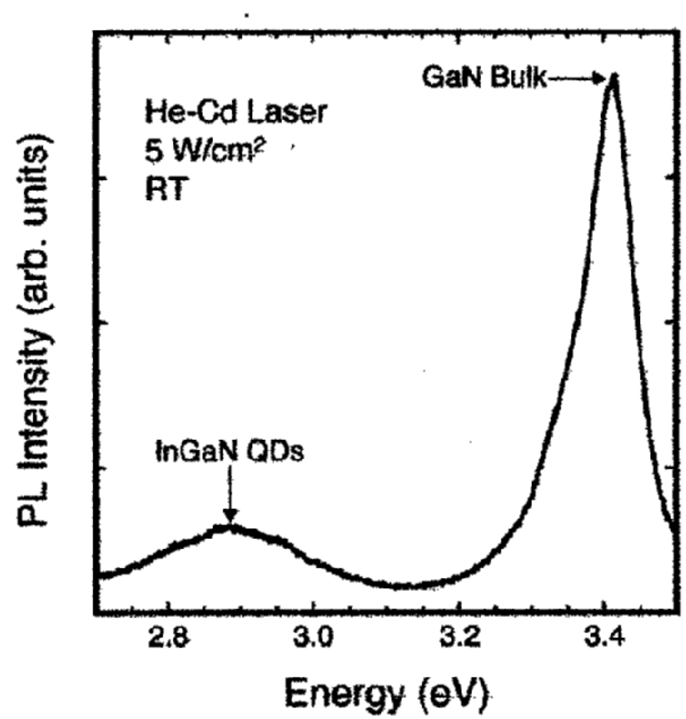
[1]S. Tanaka, S. Iwai and Y. Aoyagi, Appl. Phys. Lett. 69, 4096 (1996)

[2]O.Moriwaki, T. Somaya, K. Tachibana,S. Ishida and Y. Arakawa, Appl. Phys. Lett. 76, 2361 (2000)

[3]S. Tanaka, H. Hirayama and Y. Aoyagi, Appl. Phys. Lett. 71, 1299 (1997)

Selective area growth of InGaN QD

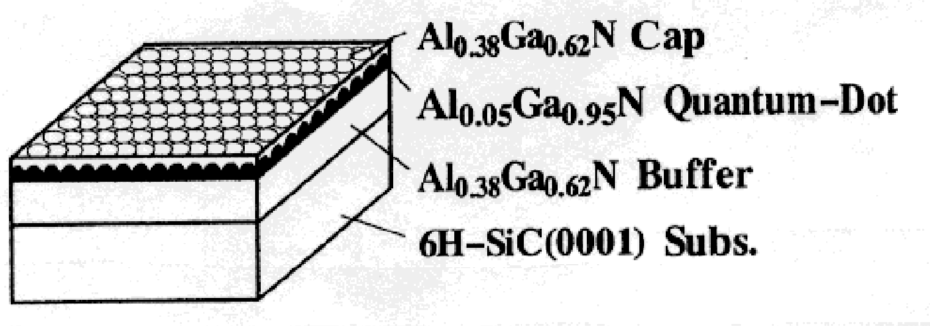


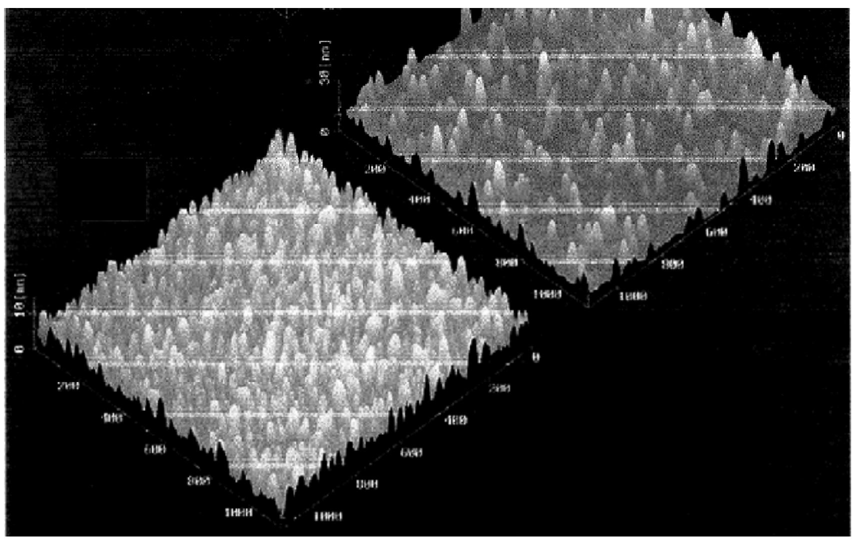


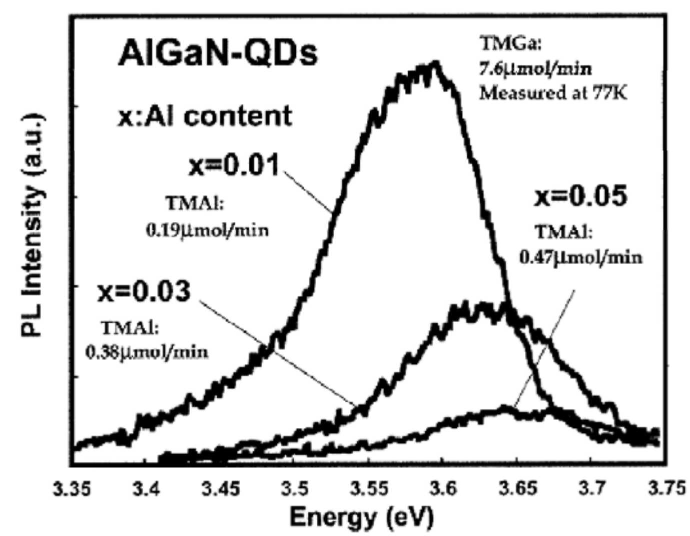
GaN pyramids were selectively grown in 4µm period and 2µm square openings in a grid-like pattern. Three period of InGaN MQW structures (30nm)were grown selectively on top of Hexagonal GaN pyramids.

K. Tachibana, T. Someya, S. Ishida, and Y. Arakawa, Appl. Phys. Lett. 76, 3212 (2000)

Self-Assembled AlGaN Quantum dots







AlGaN QD with lateral size and height of about 20nm and 6nm were obtained

H. Hirayama, Y. Aoyagi and S. Tanaka, MRS Internet JNSR 4S1, G9.4 (1999)

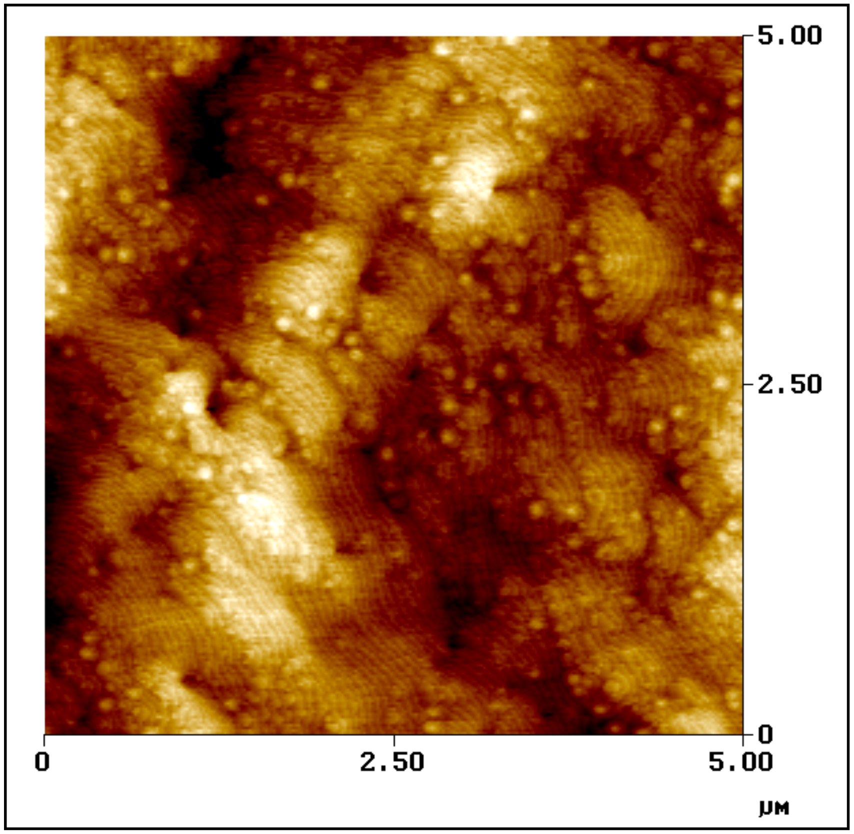
Nano-scale structure development

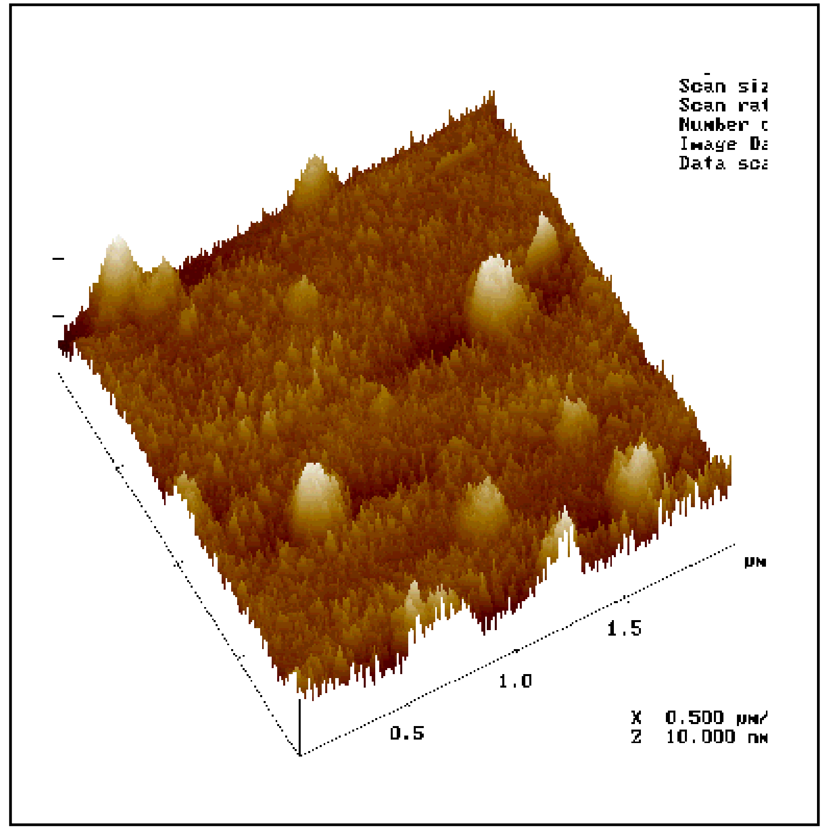
at the Center for Quantum Devices

Self-assembly

Electron beam lithography

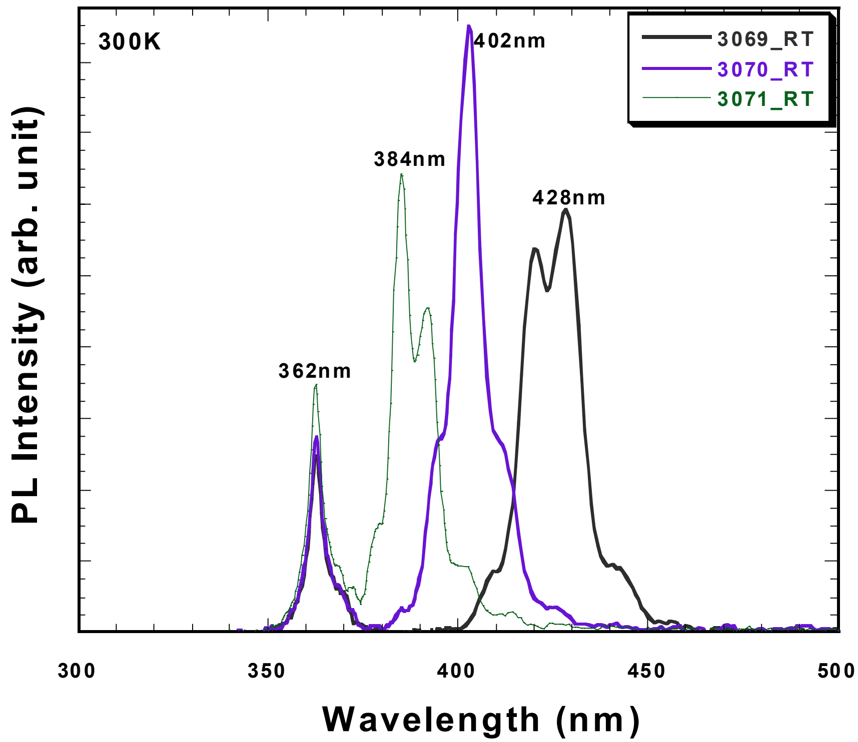
Self-Assembled InGaN Quantum dots

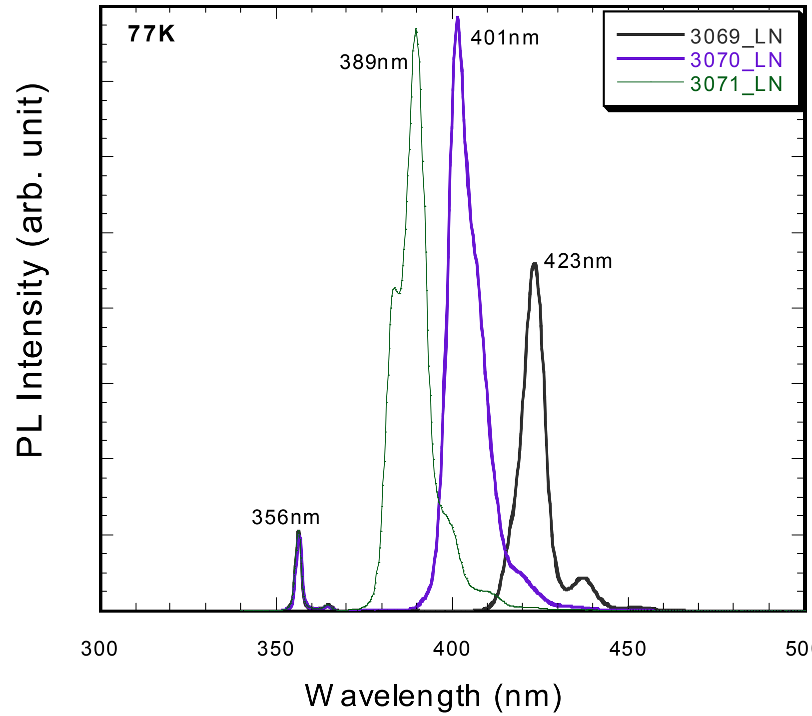




Self-assembled QD with an average width of less than 100nm and height of 10nm

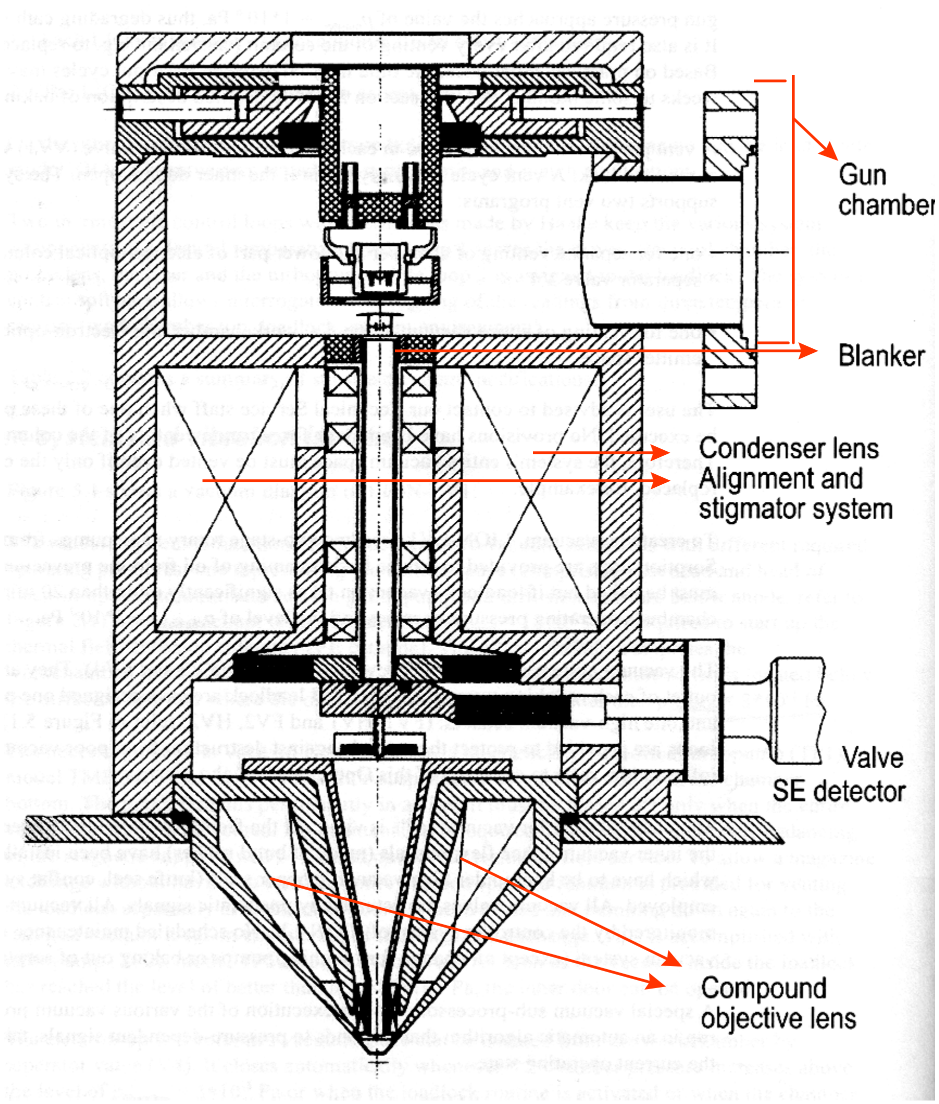
Evidence for the quantum confinement due to size effect: Photoluminescence





Dots were grown on GaN layer and embedded with GaN cap layers.

Schematic diagram of a low-voltage electron-optical column



LION-LV1 (low Voltage) e-beam lithography system provides:

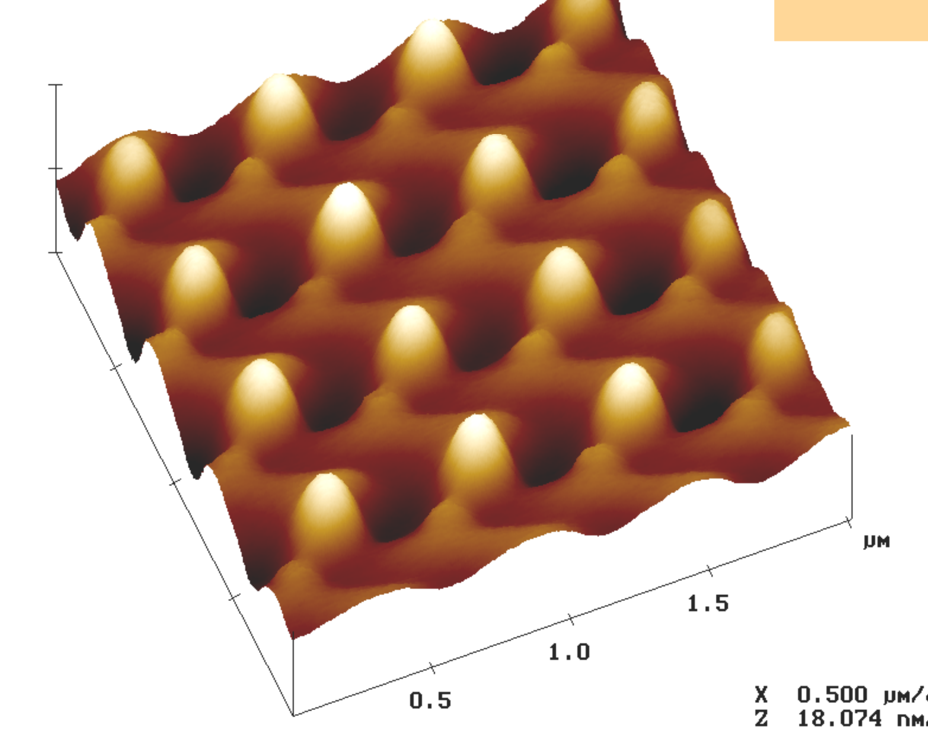
•Ultra high resolution nano-lithography (probe diameter of only 5 nm at 1KeV)

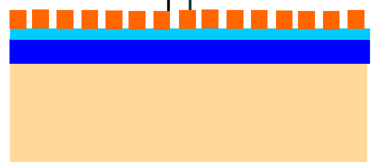
•It features electron beam energy ranging from 1KeV to 20 KeV eliminating the proximity effect due to backscattered electrons enabling imaging of small features.

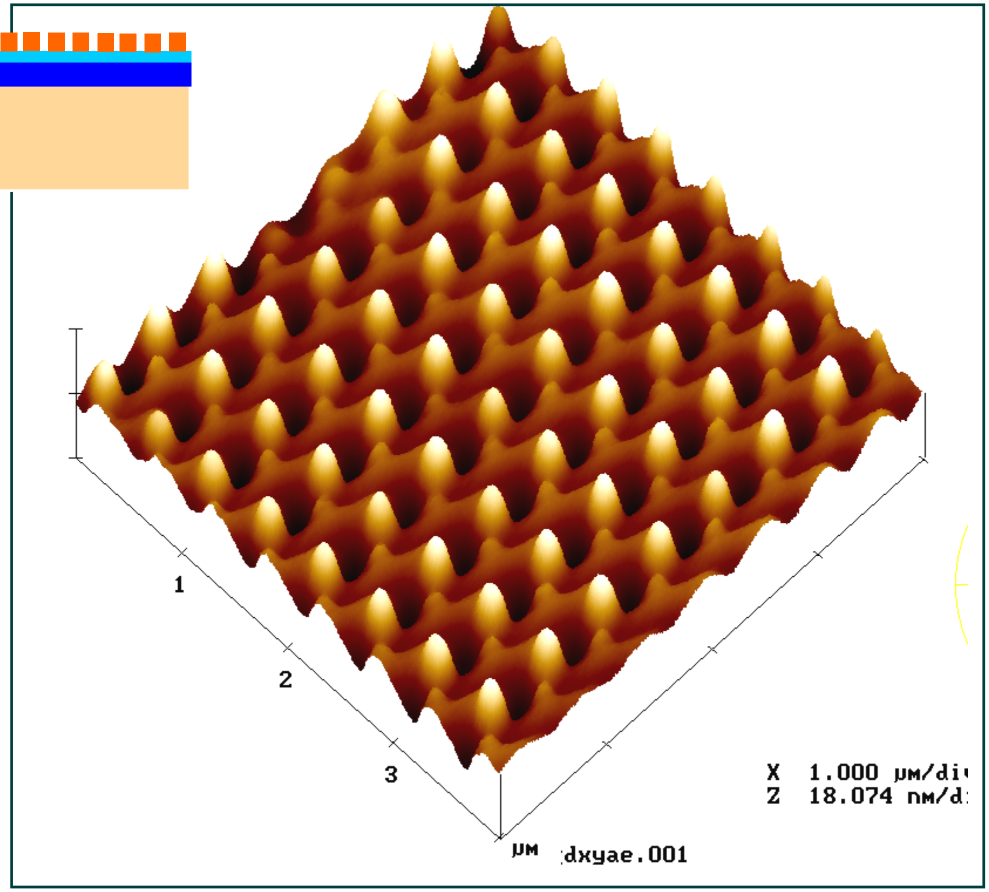
Development of uniformly distributed QD
Preliminary results

Exposure parameters:

Beam Energy: 5 kV
Probe Current: 17 pA
PMMA thickness: 200 nm

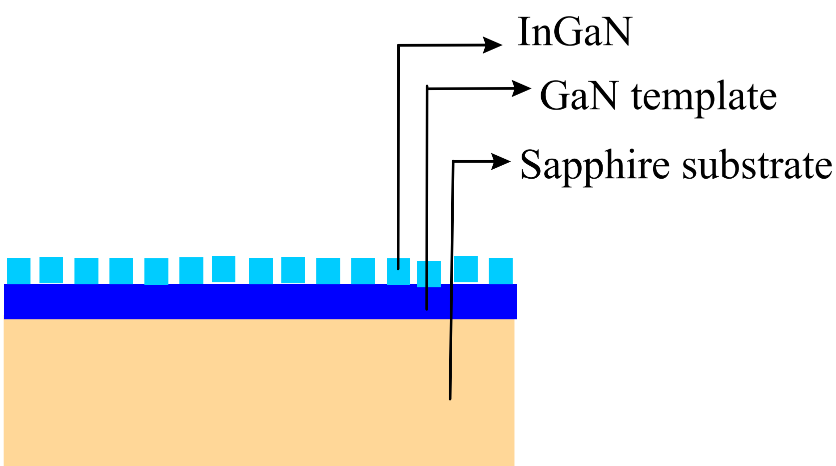


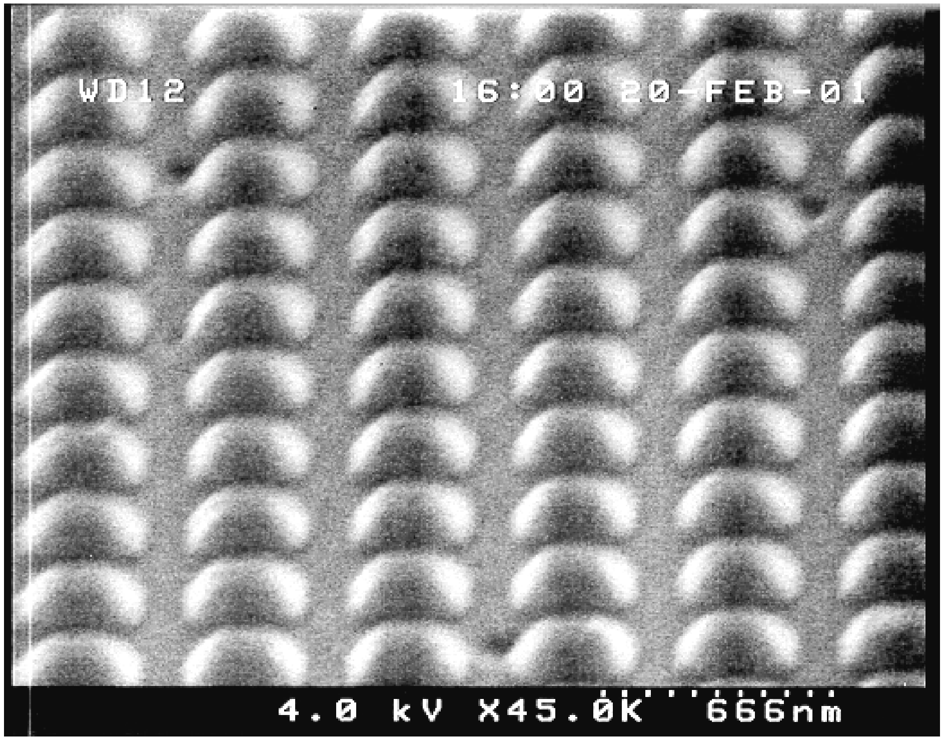




The dot profile after transferring the pattern into the mask material using dry etching.
A uniform distribution of dots of diameters smaller than 200nm can be seen.

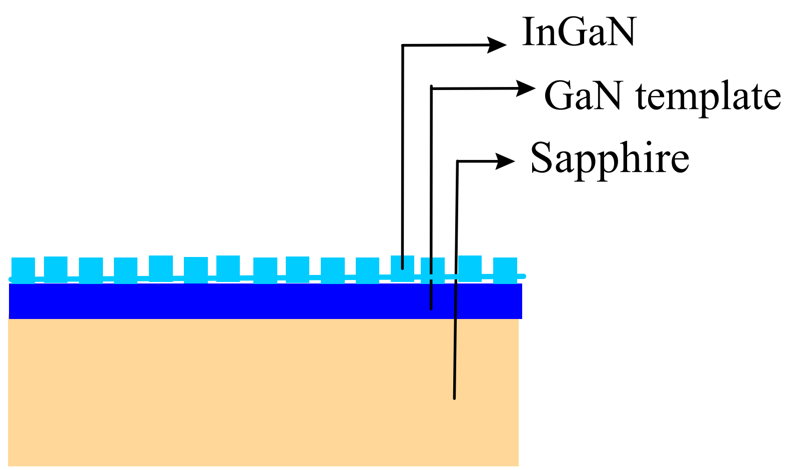
Development of uniformly distributed QD
Preliminary results

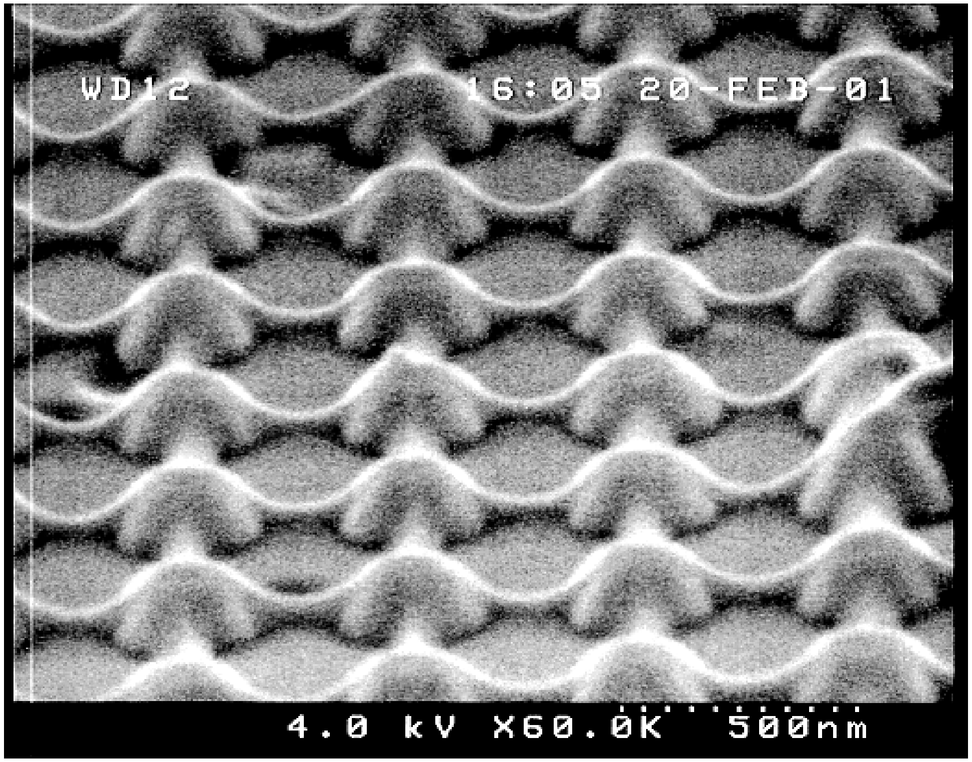




A uniform distribution of equal size dots of equally separated and of high density can be obtained after transferring the dot pattern into the InGaN material using dry etching

Development of uniformly distributed QD
Preliminary results

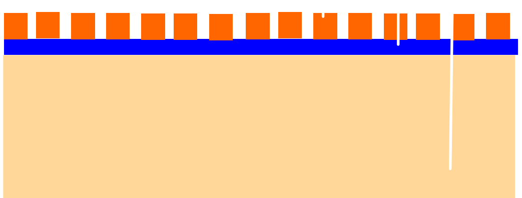




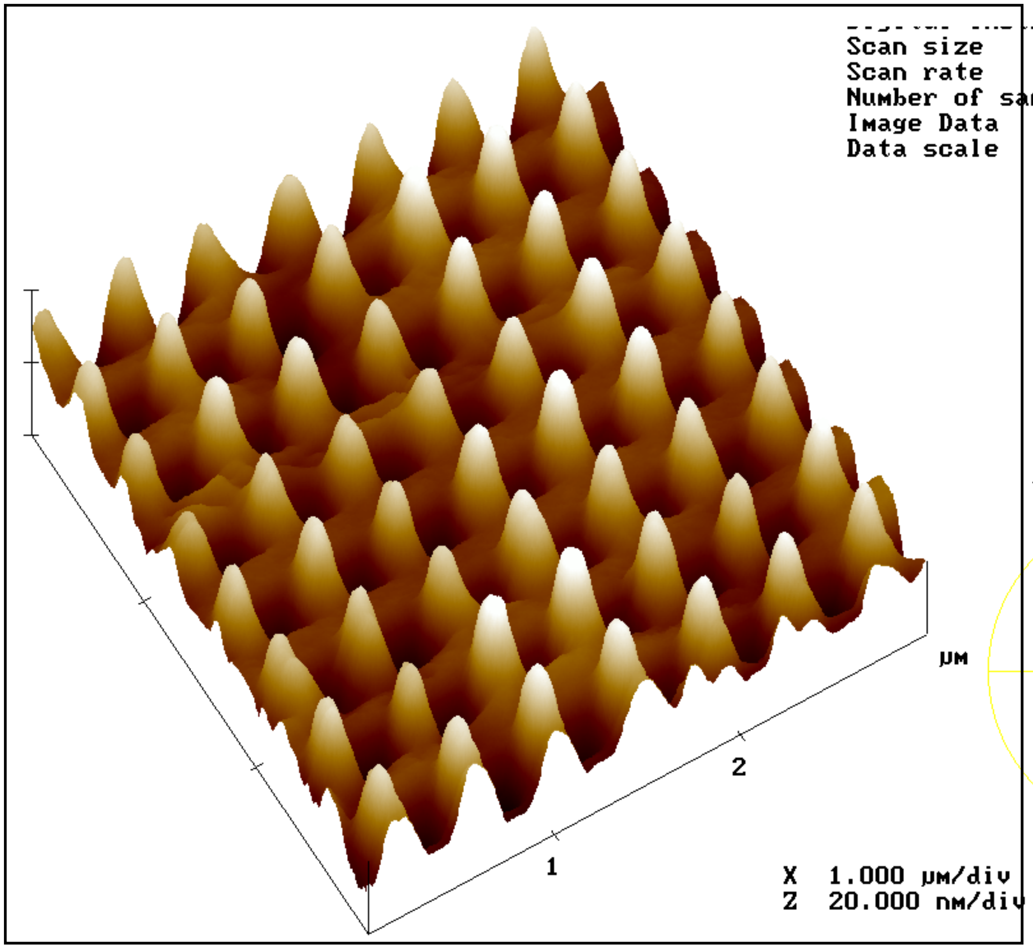
A uniform distribution of equal size dots connected to each other with wires and of high density can be obtained after transferring the dot pattern into the InGaN material using dry etching.

Development of uniformly distributed AlGaN
Preliminary results

Exposure parameters:
- Beam Energy: 5 kV
- Probe Current: 17 pA
- PMMA thickness: 200 nm



- Dielectric mask material
  - $Al_{0.10}Ga_{0.90}N$
  - Sapphire substrate

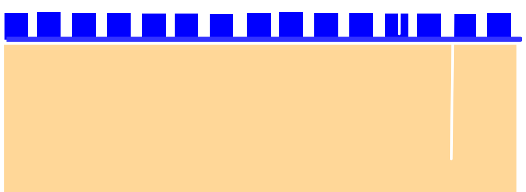


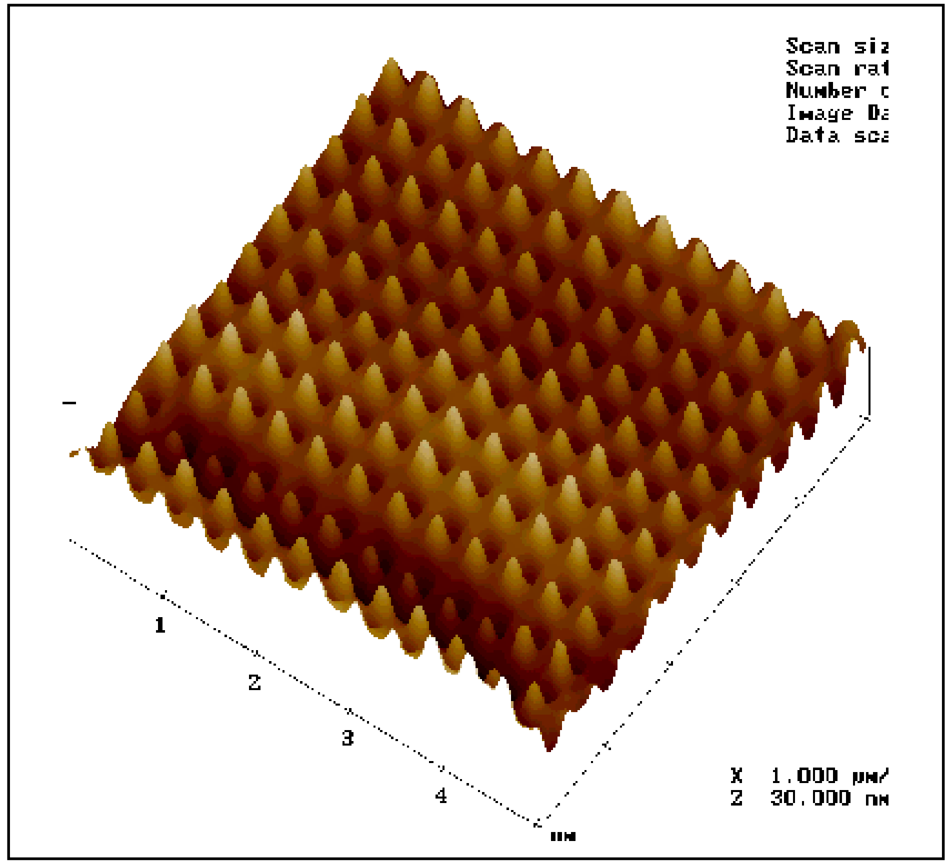
Dielectric mask with dot diameter of approximately 160nm were obtained

Development of uniformly distributed AlGaN

Preliminary results

- $Al_{0.10}Ga_{0.90}N$
- Sapphire substrate





Uniform distribution of AlGaN dots of 125 nm were obtained after RIE dry etching

Summary

• Demonstrated self-assembled InGaN Quantum Dots which exhibited blue luminescence shift due to quantum size confinement

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• Developed the technology for the fabrication of III-Nitride nano-scale structures using electron beam lithography

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• Demonstrated nano-scale GaN and AlGaN dots through electron beam lithography